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Leptogenesis in Supersymmetric Standard Model with Right-handed Neutrino *

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Abstract

We show that the leptogenesis is automatic within the supersymmetric standard model if there exist right-handed neutrinos with mass less than H_{inf}, the expansion rate during the inflation. Its scalar component grows during the inflation due to the quantum fluctuation, oscillates coherently after the inflation, and its decay generates lepton asymmetry. The scenario is naturally embedded into $SO(10)$ GUT without any modifications. We also discuss the case with heavier right-handed neutrino.

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Disclaimer

Baryogenesis [1] has been the most interesting overlapping topic in the particle physics and cosmology. The original idea of the baryogenesis using the out-of-equilibrium decay of superheavy particles in the grand unified theories (GUT) [2] is still the most popular mechanism. Meanwhile, it was found that the generation of the initial $B-L$ asymmetry is necessary rather than the baryon asymmetry B itself [3].* It was in fact pointed out that the lepton asymmetry L can be converted to the baryon asymmetry through the anomalous electroweak interactions, and the decay of the right-handed neutrino produces the initial lepton asymmetry [6]. Furthermore, the existence of the right-handed neutrino leads to non-vanishing neutrino masses [7], which can explain the solar neutrino deficit (for a combined analysis of three experiments, see [8]) via the MSW mechanism [9].

On the other hand, the supersymmetry has been regarded as an elegant mechanism to protect the huge hierarchy against the radiative corrections [10]. Since there are many scalar fields in the supersymmetric standard model, new possibilities may arise for the baryogenesis. Indeed, Affleck and Dine [11] proposed a scenario of baryogenesis where the scalar fields have large values along a flat direction at the end of the inflation, and their coherent rotation carries baryon number. Unfortunately, their original model does not create $B-L$ asymmetry.† Therefore, it is interesting to see what scenarios are possible for leptogenesis under the assumption of the supersymmetry and the existence of the right-handed neutrino.

The aim of this letter is to point out that the leptogenesis is automatic in the supersymmetric standard model if there exists a right-handed neutrino with mass M less than H_{inf}, where H_{inf} is the expansion rate of the universe at the end of the inflation.‡ During the inflation, the scalar component of the right-handed neutrino developes a large amplitude due to the quantum fluctuation [15], and it begins to oscillate after the inflation. The decay of the coherent oscillation generates lepton asymmetry, in an analogous manner as in Ref. [16]. The reheating temperature can be low enough to avoid the gravitino problem [17]. Furthermore, the scenario is naturally embedded into the $SO(10)$ GUT.

The case when the mass of the right-handed neutrino is heavier than H_{inf} is also discussed. In this case the direction $\tilde{L} = H_u$ is flat up to $\tilde{L} = H_u \lesssim (h^{-2} H_{inf}^2 M)^{1/3}$,

*There are also attempts to generate baryon asymmetry without having net $B-L$ asymmetry [3, 4, 5].

†The original model is viable when the decay of the flat direction occurs at the temperature below the electroweak phase transition.

‡There is an upperbound $H_{inf} < 2.7 \times 10^{14}$ GeV [12] using the COBE data [13] where the bound is saturated when the gravitational radiation dominates the density fluctuation. One may have significantly smaller H_{inf} if the scalar fluctuation dominates [14], but most of the models predict $H_{inf} \geq 10^{12}$ GeV [12].

which has a lepton-number violating operator $\frac{h^2 m}{M}(\tilde{L}H_u)^2$. Here, h is the Yukawa coupling constant in the superpotential $W = hLH_uN$, and m is the supersymmetry breaking mass. If the scalar fields grow along this direction during the inflation, then leptogenesis occurs *á la* Affleck–Dine.

Our starting point is the supersymmetric standard model with three generations of right-handed neutrinos.[§] Let us assume that (at least) one of the right-handed neutrinos, say that of the first generation, is lighter than H_{inf}. The quantum fluctuation of the scalar field ϕ with mass M is [15]

$$\langle \phi^2 \rangle \simeq \frac{3}{8\pi^2}\frac{H_{inf}^4}{M^2}, \tag{1}$$

with a coherence length

$$l \sim H_{inf}^{-1} \exp\left(\frac{3H_{inf}^2}{2M^2}\right). \tag{2}$$

The scalar field becomes coherent over super-horizon distances if $M < H_{inf}$, which can be regarded as a classical constant field. Therefore, the right-handed sneutrino of the first generation $\tilde{N}$ becomes a coherent classical field if $M < H_{inf}$, and can have a large value of $\tilde{N} \sim H_{inf}^2/M$ at the end of the inflation.[¶] During the reheating process, the expansion rate rapidly decreases, and the right-handed sneutrino begins to oscillate around the origin. The coherent oscillation decays into $L\tilde{H}_u$ or $\tilde{L}H_u$ and their CP-conjugates when $t \simeq \Gamma_N^{-1}$, producing the lepton number density

$$n_L = \epsilon M |\tilde{N}|^2. \tag{3}$$

Here $|\tilde{N}|$ is the amplitude of the coherent oscillation, and ϵ is the CP-asymmetry in the sneutrino decay into leptons and anti-leptons [6, 16].

The fate of the generated lepton asymmetry depends on the lifetime of the inflaton Γ_ψ^{-1}. Assuming the initial value of the right-handed sneutrino $\tilde{N}_0$ is smaller than the Planck mass M_P, the coherent oscillation of the sneutrino does not dominate the energy density of the universe during the reheating process. Then there are three possible cases: (1) $\Gamma_N > \Gamma_\psi$ so that $\tilde{N}$ decays during the reheating process, (2) $\Gamma_N < \Gamma_\psi < \Gamma_N (M_P/\tilde{N}_0)^4$ so that $\tilde{N}$ decays after the reheating, but without dominating the energy density of the universe, and (3)

[§] At least two right-handed neutrinos are required to have CP-violation in the Yukawa coupling.

[¶] Even for the gauge non-singlet scalar fields ϕ with D-term potential, it is natural to expect $\phi \sim H_{inf}$ during the inflation, though their coherence length is short, $l \sim H_{inf}^{-1}$. Then the right-handed sneutrino of third generation cannot acquire a large value due to its large coupling to slepton and Higgs fields, even if it is lighter than H_{inf}. The right-handed sneutrinos both of first and second generations can grow during the inflation even when all the other fields are fluctuating at $O(H_{inf})$. We discuss that of the first generation only for simplicity.

$\Gamma_\psi > \Gamma_N (M_P/\tilde{N}_0)^4$ so that $\tilde{N}$ dominates the universe after the reheating before its decay. The yield of the lepton asymmetry $Y_L = n_L/s$ is calculated as

(1) $Y_L = \epsilon \dfrac{\tilde{N}_0^2}{M M_P} \left(\dfrac{\Gamma_\psi}{M_P}\right)^{1/2}$,

(2) $Y_L = \epsilon \dfrac{\tilde{N}_0^2}{M M_P} \left(\dfrac{\Gamma_\psi}{M_P}\right)^{1/2}$,

(3) $Y_L = \epsilon \dfrac{(M_P \Gamma_N)^{1/2}}{M}$,

for each cases. The expressions for the temperature at the sneutrino decay T_{dN} are different for each cases, such as

(1) $T_{dN} = (M_P^2 \Gamma_\psi \Gamma_N)^{1/4}$,

(2) $T_{dN} = (M_P \Gamma_N)^{1/2}$,

(3) $T_{dN} = (M_P \Gamma_N)^{1/2}$.

For the produced lepton asymmetry to be converted to the baryon asymmetry by the electroweak anomaly, T_{dN} has to be larger than the critical temperature of the electroweak phase transition. This puts constraints on model parameters. For instance, take values like $\epsilon = 10^{-3}$, $M = 10^{10}$ GeV, $h = 10^{-5}$, $\Gamma_N = h^2 M/8\pi \simeq 0.1$ GeV, $m_\psi = 10^{13}$ GeV, $\Gamma_\psi = m_\psi^3/M_P^2 \simeq 10$ GeV, and $\tilde{N}_0 \simeq 10^{16}$ GeV,[‖] the case (2) is realized, and we obtain $Y_L = 3 \times 10^{-10}$, and $T_{dN} = 10^9$ GeV. Note that the final baryon asymmetry Y_B is related to the initial lepton asymmetry by $Y_B = 0.35 Y_L$, which is consistent with the value required from the nucleosynthesis, $Y_B = 0.6$–1×10^{-10}. Furthermore, T_{dN} is high enough so that the lepton asymmetry is converted to baryon one while the reheating temperature $T_{RH} \simeq \sqrt{\Gamma_\psi M_P} \simeq 10^{10}$ GeV is low enough to avoid the gravitino problem [17].

So far we discussed the supersymmetric standard model with right-handed neutrinos. We are tempted to embed the whole scenario into $SO(10)$ GUT since there the existence of the right-handed neutrino is natural. It seems, however, not easy to implement the scenario into the $SO(10)$ GUT at the first sight, since $\tilde{N}$ acquires the D-term potential due to the $SO(10)$ gauge interactions. Suppose the D-term potential is $V \sim g^2 |\tilde{N}|^4$, it has a self-mass $M_{self}^2 \sim g^2 |\tilde{N}|^2$. Then its maximum possible value is only $|\tilde{N}| \sim H_{inf}$, and its coherence length is short, $l \sim H_{inf}^{-1}$. Thus it cannot be regarded as a coherent field over many horizons.

[‖] We will discuss later that $\tilde{N}$ can grow up to the GUT-scale even in the $SO(10)$ model.

Our crucial observation is that the D-term decouples from the potential of $\tilde{N}$ as far as the value of $\tilde{N}$ is smaller than the $SO(10)$ breaking scale. Then the whole scenario can be extended to $SO(10)$ GUT without modifications, despite the first glance. We will show below with an explicit example that the scalar partner of the Nambu–Goldstone boson automatically shifts to absorb the non-vanishing D-term of $\tilde{N}$, and the D-term potential decouples (for a general discussion on the decoupling of the D-term potential, see Ref. [18] for example).

Suppose $SO(10)$ is broken down to $SU(5)$ by the condensation of the $SU(5)$ singlet components in the $\phi(\mathbf{126})$ and $\bar{\phi}(\mathbf{126}^*)$ representations,**

$$\langle \phi_{\mathbf{1}} \rangle = \langle \bar{\phi}_{\mathbf{1}} \rangle = v, \tag{4}$$

where the subscript $\mathbf{1}$ denotes the $SU(5)$ singlet components, and vacuum expectation values of $\phi_{\mathbf{1}}$, $\bar{\phi}_{\mathbf{1}}$ are assumed to take $v \sim 10^{16}$ GeV for definiteness of the discussions. For example, we assume the superpotential as

$$W = k(\phi\bar{\phi} - v^2)\chi, \tag{5}$$

with a singlet superfield χ.†† One also has to add a term to the superpotential which gives the mass of the right-handed neutrino,

$$W_N = f\phi\psi\psi, \tag{6}$$

where $\psi(\mathbf{16})$ is the matter multiplet and f is a coupling constant. The right-handed neutrino mass is given by $M = 2fv$. The $\phi_{\mathbf{1}}$ and $\bar{\phi}_{\mathbf{1}}$ fields are expanded around the minimum,

$$\phi_{\mathbf{1}} = v + \frac{1}{2}(\varphi + i\eta), \tag{7}$$

$$\bar{\phi}_{\mathbf{1}} = v - \frac{1}{2}(\varphi + i\eta), \tag{8}$$

where η is the true Nambu–Goldstone field which is absorbed into the gauge field, and φ is its scalar partner. We will focus on φ hereafter.

During the inflation, all the fields with GUT-scale mass rapidly drop into their stationary points, including ϕ. On the contrary, the right-handed sneutrino field is light compared to the expansion rate, and we adopt the adiabatic

**The discussions are not altered qualitatively when the $SO(10)$ is broken by $\mathbf{16}$ representation Higgs multiplet. The only difference is that the right-handed neutrino mass comes from a non-renormalizable interaction between Higgs $\mathbf{16}$ and matter $\mathbf{16}$ multiplets.

††It is necessary to arrange the superpotential to get rid of unwanted massless fields. An example is to introduce $\xi(\mathbf{16})$ and $\bar{\xi}(\mathbf{16}^*)$, and take a superpotential $W = M\bar{\phi}\phi + M'\bar{\xi}\xi + g(\phi\xi\xi + \bar{\phi}\bar{\xi}\bar{\xi})$. However, the precise form of the superpotential is irrelevant to our discussions, and we took the simplest possible form.

approximation to keep $\tilde{N}$ fixed, and solve for φ. The potential in the φ and $\tilde{N}$ space is

$$V = g^2 \frac{5}{16}(4v\varphi + |\tilde{N}|^2)^2 + \frac{k^2}{16}\varphi^4 + M^2|\tilde{N}|^2 \left(\left(1 + \frac{\varphi}{2v}\right)^2 + \left|\frac{\tilde{N}}{2v}\right|^2 \right), \qquad (9)$$

where the first term is the D-term potential, and we have used $M = 2fv$. Since φ has a mass $\simeq gv$ from the D-term, it rapidly drops into the minimum, $\varphi = -|\tilde{N}|^2/4v + O(|\tilde{N}|^6)$, and it stays at this minimum during the slow rolling of the $\tilde{N}$ as far as $|\tilde{N}| < v$. Then the potential for $\tilde{N}$ alone reads

$$V = M^2|\tilde{N}|^2 + \frac{M^2|\tilde{N}|^6}{64v^4} + O(|\tilde{N}|^8). \qquad (10)$$

Therefore, the potential remains essentially the same as in the non-$SO(10)$ case up to $\tilde{N} \sim v$.[‡‡] $\tilde{N}$ can grow up to the GUT-scale v during the inflationary epoch, and has a super-horizon size coherence length $l \sim H_{inf}^{-1} \exp(3H_{inf}^2/2M)$.

It is an interesting question what occurs when the right-handed neutrino is heavier. An intriguing possibility is that the right-handed sneutrino itself is the inflaton [16], which is possible when $M = H_{inf} \simeq 10^{13}$ GeV. In this scenario, right-handed sneutrino has a large value $\gg M_P$ at the birth of the universe, and rolls slowly down the potential, thereby driving the chaotic inflation. The reheating process itself produces lepton asymmetry just as in the previous scenario. However, it is very difficult to embed this scenario in the $SO(10)$ GUT, since the D-term potential protects $\tilde{N}$ to have such a large value.

If the right-handed neutrino is further heavier, $M > H_{inf}$, it rapidly drops into its stationary point during the inflation. On the other hand, the direction $\tilde{L} = H_u$ is flat up to to $\tilde{L} = H_u \lesssim (h^{-2}H_{inf}^2 M)^{1/3}$ as shown below. Therefore, the scalar fields may become coherent along this direction during the inflation.[*] The potential of $\tilde{L}$, H_u, and $\tilde{N}$ reads as

$$\begin{aligned} V &= \left|h\tilde{L}H_u + M\tilde{N}\right|^2 + \left|h\tilde{L}\tilde{N}\right|^2 + \left|hH_u\tilde{N}\right|^2 + \frac{g_Z^2}{8}(|\tilde{L}|^2 - |H_u|^2)^2 \\ &\quad + \left(Ah\tilde{L}H_u\tilde{N} + \frac{1}{2}BM\tilde{N}^2 + c.c.\right) + m_L^2|\tilde{L}|^2 + m_H^2|H_u|^2. \end{aligned} \qquad (11)$$

[‡‡]The disappearance of the $|\tilde{N}|^4$ term is an accident in this example. There appear terms like $\frac{M^2}{v^2}|\tilde{N}|^4$ in general, but the conclusion remains the same.

[*]This direction is flat only when other fields such as scalar top $\tilde{t}$ vanish. It might be problematic when $\tilde{t} \sim H_{inf}$ during the inflation. It is, therefore, not clear to us whether the scalar fields grow to a particular direction during the inflation. This is a general problem inherent in the Affleck–Dine scenario. We take conservatively $\tilde{L} = H_u \simeq O(H_{inf})$ at the end of the inflation for later estimation.

Here, the SUSY-breaking terms A, B, m_L, m_H are all of the order of the weak-scale, h is the Yukawa coupling, $g_Z = e/\sin\theta_W \cos\theta_W$, and we restricted ourselves to the neutral components in $\tilde{L}$ and H_u. Since it is assumed $M > H_{inf}$, $\tilde{N}$ rapidly drops into the minimum

$$\tilde{N} = -\frac{h\tilde{L}H_u}{M^2 + |h\tilde{L}|^2 + |hH_u|^2}, \tag{12}$$

while $\tilde{L}$ and H_u can be treated adiabatically. We can expand the potential in terms of $h\tilde{L}/M$ and hH_u/M, and then the potential reads as

$$\begin{aligned} V &= \frac{h^4}{M^2}|\tilde{L}H_u|^2(|\tilde{L}|^2 + |H_u|^2) + \frac{g_Z^2}{8}(|\tilde{L}|^2 - |H_u|^2)^2 \\ &\quad - \left(\frac{h^2(A-B)}{M}(\tilde{L}H_u)^2 + c.c.\right) + m_L^2|\tilde{L}|^2 + m_H^2|H_u|^2. \end{aligned} \tag{13}$$

There are two crucial points in this potential. One is that the disappearance of the $|h\tilde{L}H_u|^2$ term in the potential which might have destroyed the flatness if existent. The potential remains $V \lesssim H_{inf}^4$ up to $\tilde{L} \lesssim (h^{-2}H_{inf}^2 M)^{1/3}$. Therefore, the potential is flat even for third generation $\tilde{L}$. The other is that there automatically arises lepton-number violating operator $\frac{h^2(A-B)}{M}(\tilde{L}H_u)^2$.[†] Therefore, this model is an ideal and so-far the simplest realization of the Affleck–Dine mechanism.[‡] We have checked that the following parameters give the lepton asymmetry $Y_L \simeq 10^{-8}$ according to the estimation in Ref. [20]: $M = 10^{16}$ GeV, $\Gamma_\psi = 10$ GeV, $m = 10^3$ GeV, $h = 1$, and the initial value $\tilde{L} = H_u \simeq H_{inf}$ with $O(1)$ phase factor.

In summary, we found that the leptogenesis is automatic within the supersymmetric models if there exist a right-handed neutrino lighter than H_{inf}. Its scalar component grows during the inflation, oscillates coherently after the inflation, and its decay generates lepton asymmetry. The reheating temperature can be low (typically $T < 10^{10}$ GeV), which is welcome to avoid the gravitino problem. Furthermore, the scenario is naturally embedded into $SO(10)$ GUT without any modifications. For heavier right-handed neutrino, leptogenesis via Affleck–Dine mechanism may be possible, if the scalar fields grow along the $\tilde{L} = H_u$ direction during the inflation.

[†]Note that the existence of the right-handed neutrino is not a necessity in this scenario. The only requirements are that the flat direction $\tilde{L} = H_u$ remains flat up to a large scale, and there is a lepton-number violating operator $(\tilde{L}H_u)^2$.

[‡]The authors of Ref. [19] also pointed out that the leptogenesis is possible *á la* Affleck–Dine when the R-parity is explicitly broken and one uses an effective operator which arises at the three-loop level.

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